Measured daylighting potential of a static optical louver system under real sun and sky conditions

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Abstract

By utilizing highly specular surfaces and engineered geometry, optical sunlight redirecting systems integrated into the overhead "clerestory" zone of the building facade present the potential to enlarge the daylighting zone by redirecting the luminous flux incident on the window deeper into the space than conventional shading systems. In addition, by developing system geometry to redirect daylight to specific regions within the space, optical light redirecting systems have the potential to avoid the glare conditions commonly produced by conventional facade shading systems that diffuse significant amounts of daylight below head height into the occupant's field of view.

In this case study, side-by-side comparisons were made between an optical louver system (OLS) and a conventional Venetian blind located inboard of a south-facing, small-area, clerestory window in a full-scale office testbed. Daylight autonomy (DA), window luminance, and ceiling luminance were used to assess performance. The performance of both systems was found to have significant seasonal variation, where performance linearly improved as maximum solar altitudes transitioned from summer to winter solstice under clear sky conditions. Although the OLS produced fewer hours (between 0.25 to 1.5 h) per day of DA than the horizontal Venetian blind, the OLS never exceeded the designated 2000 cd/m^2 threshold for window glare. In contrast, the Venetian blind, which was set a horizontal slat angle, significantly exceeded this threshold between 61% and 80% of the day for clear sky conditions over the test interval. Ceiling luminance was analyzed using calibrated high dynamic range luminance images. Under clear sky conditions, the OLS was found to produce a more uniform luminance distribution over the depth of the room as well as significantly increase the luminance of the ceiling during the middle of the day (10:00-14:00). Performance was comparable to or slightly worse when the surface solar azimuth was greater than approximately ±45° from the facade normal. The OLS always occluded direct sun but blocked direct views to the outdoors.

Keywords: daylighting, sunlight redirecting system, optical louver system, field measurements, high dynamic range luminance images

1. Introduction

A commonly cited objective of daylighting strategies is the delivery of sufficient illumination from windows to eliminate the need for supplemental illumination from electrical lighting. Functional subdivision of the window wall into a lower "view" zone and an upper "clerestory" zone for daylight transmission is a common strategy to achieve this goal. Because occupants often reduce the daylight transmission of the lower zone using shading devices to maintain comfortable visual conditions, the upper zone is designed to serve as the primary means of daylight delivery to the space. For single occupancy offices, this strategy is effective. Due to the office depth, typically 3.05 m to 6.1 m (10-20 ft), the occupant is located relatively close to the window wall and the clerestory is not within the occupant's primary field of view. Because many occupants working in open plan offices are located at a greater distance from the facade, the relatively lower ambient light levels combined with a more direct view of the bright clerestory can cause uncomfortable luminance contrasts, leading to the deployment of shading devices to maintain visual comfort. As an example, in a number of case study evaluations conducted in the U.K., Bordass et al. [1] noted that tall windows intended to enable greater daylight penetration to open plan workspaces were often found with the shades closed and the electric lights turned on. Bordass reported that the cause of the default state of "shades down, lights on" was the need to resolve the visual discomfort experienced by those who worked the farthest distance from the facade and did not have control over the shades.

In addition to the unnecessary use of electrical lighting that can result from the shading of clerestory windows, electric lights may be switched on by occupants in daylit spaces even when sufficient illumination is provided by windows because the contrast in luminance between surfaces adjacent to the facade and surfaces away from the facade causes the space to appear dark or "cave-like" to occupants. With the increasing trend of open plan workspaces designed to comply with the daylight illuminance criteria specified in green building rating systems (e.g., Leadership in Energy and Environmental Design (LEED), BRE Environmental Assessment Method (BREEAM)), daylighting strategies need to be responsive to human factors issues of visual comfort and luminance uniformity in addition to providing sufficient illumination for task visibility.

The goal of this study was to compare the daylighting potential of an OLS installed in the clerestory region of a facade against a conventional Venetian blind over seasonal changes in sun and sky conditions to test if the optical surface treatment and specific geometry of the OLS consistently resulted in useful daylight illuminance levels and reduced visual discomfort.

2. Measurements and Procedures

2.1. Experimental set-up

Experimental tests were conducted in the Window Testbed Facility located at the Lawrence Berkeley National Laboratory (LBNL) in Berkeley, California (latitude 37°4'N, longitude 122°1'W). The facility consists of three, identical, south-facing, side-by-side, furnished test rooms built to represent a commercial private office. The test rooms were unoccupied during this study. Interior surface reflectances of the floor, walls, and ceiling, are 0.18, 0.85, and 0.86, respectively, as measured by a Minolta CM-2002 spectroreflectometer. Obstructions to the windows were minor.

For these tests, all areas of the window wall, with the exception of the clerestory opening (**Fig. 1**), were completely occluded with black-out cloth. The clerestory opening was 2.65-m- (8.69-ft-) wide by 0.762-m- (2.5-ft-) tall and glazed with two, dual-pane, low-emittance windows (type = VRE 15-67 glass; Tv=0.62, Rvb=0.256) separated by a 63.5-mm- (2.5-in-) wide vertical mullion. The window area to wall ratio (WWR) of the vision portion of the window was 0.174, assuming a floor-to-floor height of 3.81 m (12.5 ft). Testing was conducted with the electrical lighting turned off.

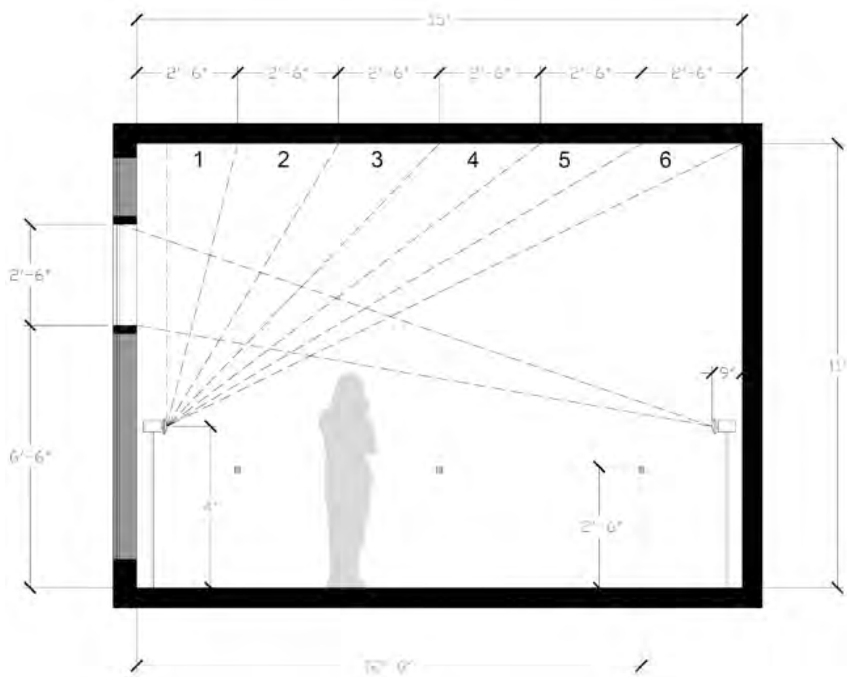

Fig. 1. *Cross-sectional view of the test office showing the unblocked clerestory region, location of photosensors and digital cameras. Also shown is the subdivision of the ceiling into six equal regions for the luminance analysis.*

The OLS is a commercial product (LightLouver™ Daylighting System), consisting of 65-mm- (2.56-in-) deep, vertically-stacked, concave-up, polished mirrored louvers (approximately 85% total reflectance) (**Fig. 2**). The louver geometry was designed to redirect incident sunlight uniformly onto the ceiling and to block sunlight redirected below head height that would cause glare. The system completely obstructs view to the outdoors. The system is static, requiring no adjustment over the year, and was placed within the framed opening of the window, almost flush against the face of the glass.

Fig. 2*. Left: Side view of the OLS prior to being installed on the inward face of the clerestory glazing. The unit is slid on the horizontal brackets at the top of the OLS into the frame cavity. Middle: Interior view of the OLS. Right: Interior view of the Venetian blind reference condition installed.*

The OLS was compared to a static, horizontal Venetian blind reference condition. The Venetian blind consisted of single, 0.025-m- (1-inch-) wide slats with a matte white coating in a fully lowered position covering the entire clerestory aperture **(Fig. 2**). The blind was installed inboard of the window framing, 133-mm- (5.25-in-) from the face of the glass. Slat angles were maintained at a horizontal position throughout the testing to represent "best case" conditions for a typical clerestory window.

2.2. Measured data

Two types of measurements were used in this study. The first was illuminance recorded at the workplane at distances of 0.762-m- (2.5-ft-), 2.286-m- (7.5-ft-), and 3.81-m- (12.5-ft-) from the facade and 0.762-m- (2.5-ft-) above the floor using photometric sensors (type=Licor LI-210, nominal accuracy = 3%, range = 0 - 15,000 lux) at 1-min intervals. Exterior obstructions varied across the testbed facility. Differences in average workplane illuminance were within 2.6% between rooms over a 4-hour interval and within 1.4% over a 12-hour interval (**Fig. 3**).

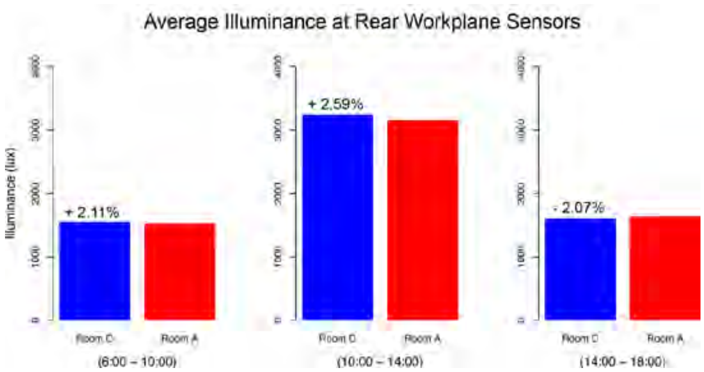

Fig. 3*. Comparison in average workplane illuminance between test rooms for one day under clear sky conditions with all windows in the test rooms unshaded (October 28, 2009). Each bar indicates the average of both photosensors located 3.81-m- (12.5-ft-) from the facade for each 4-hour subinterval. Annotation (in %) on each bar indicates the percentage increase or decrease in average illuminance of room C (OLS) over room A (Venetian blind) for each respective interval.*

Second, luminance maps were time-lapse acquired every 5 min from two digital CCD cameras located in each test room as shown in **Fig. 1**. High dynamic range (HDR) luminance maps store luminance data on a "per-pixel" scale, enabling the variation in scene luminance from a specific viewpoint to be quantified and analyzed. A more complete description of the system is given in [2]. Measurement errors were estimated to be within ±6% on average of reference measurements within a range of 0-11,000 cd/m^2 [2].

Data were acquired from 6:00 to 18:00 Standard Time (ST) from February 6, 2010 to August 2, 2010. During this period, the OLS and reference Venetian blind were tested on a rotational schedule to accommodate other test conditions, resulting in a total of 31 test days. As a result of technical issues with the installation, no data were collected between March 1 and April 30.

Sky conditions were expected to have a significant influence on performance outcomes. Therefore, a sky classification for each test day was determined using the method developed by [3]. The classification is based on two parameters: 1) the fraction of time, $\boldsymbol{s}$, that the direct normal irradiation[1] exceeds 120 W/m^2, and 2) $\boldsymbol{U}$, the natural logarithm of the average of the absolute values of the change in global horizontal illuminance (lux) over a one-minute span. If $\boldsymbol{s}$ is less than 0.03, then conditions are considered to be overcast. If $\boldsymbol{s}$ is greater than or equal to 0.75, conditions are characterized as clear. For solar fractions between this range, if $\boldsymbol{U}<(10 - 6s)$, conditions are considered cloudy. Otherwise, conditions are considered dynamic. The resulting number of test days and sky conditions are summarized in **Fig. 4**.

[1] Direct normal irradiance was measured using a pyroheliometer.

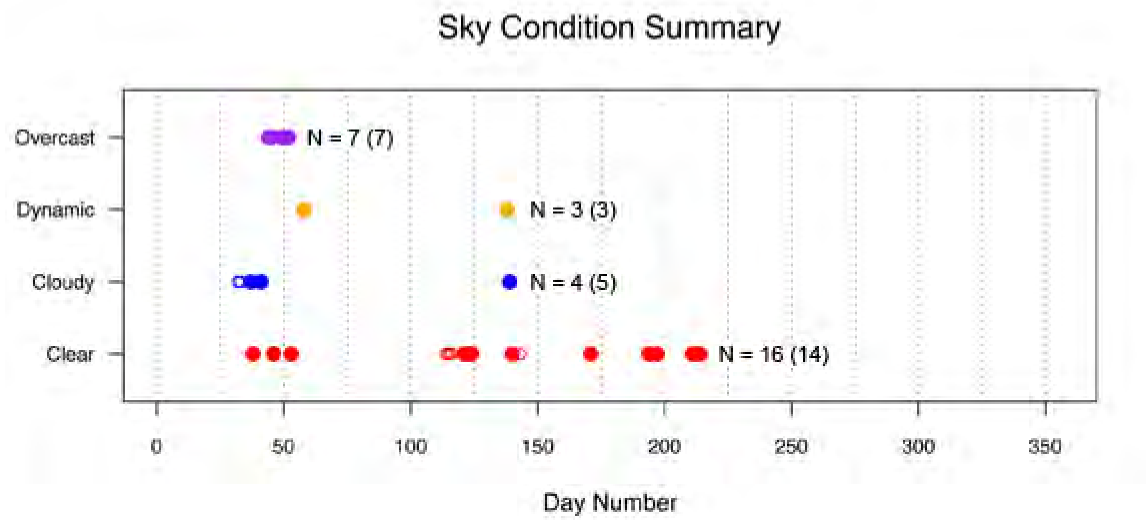

***Fig. 4**. Classification and distribution of sky conditions during the test period. Values of "N" in parentheses indicate the number of days where both the test and reference condition had usable luminance data. Values of "N" outside of parentheses indicate the number days when workplane illuminance data were available.*

2.3. Performance metrics

Daylight autonomy (DA) is a general measure of daylight sufficiency and has been computed in various ways by the daylighting community over the past decade, a reference of which is given in [4]. DA is basically a measure of when the task illuminance setpoint can be maintained by daylight alone. In this study, DA was computed as the percentage of day (6:00-18:00, inclusive of nighttime periods) when the workplane illuminance setpoint of 100 lux or 500 lux was satisfied by daylight at the two rear workplane illuminance sensors, 3.81 m (12.5 ft) from the facade (**Fig. 1**). Since the rear of the room typically receives the least amount of daylight, this metric is intended to be an indication of the percentage of day when 100% of the floor area met the setpoint level.

Average window luminance was computed from the HDR luminance images for each of the two upper window panes. Because the average luminance between regions was not found to vary significantly at any given time, the average of the two regions was used. Luminance levels were compared to a maximum value of 2000 cd/m^2 based on the Illuminating Engineering Society of North America (IESNA) guidelines for acceptable levels of non-uniformity. This is expressed in terms of luminance ratios between surfaces in the field of view. The basis for the guideline is the physiological phenomenon called transient adaptation, a phenomenon associated with reduced visibility after viewing a higher or lower luminance than that of the task [5]. To avoid visual performance decrements, a maximum allowable contrast of [1:3:10] is permitted between the task, surroundings, and background. In this study, the visual task was defined as a visual display terminal (VDT) with a constant luminance of 200 cd/m^2. The clerestory region was assumed to be a source of visual discomfort if it exceeded the luminance of the task by a factor of 10 (i.e., 1:10 ratio for "background region"), leading to the maximum allowable luminance of 2000 cd/m^2.

The delivery of daylight from overhead has the benefit of providing room illumination without the glare that is commonly associated with sidelighting. In this study, ceiling luminance was considered as a source of "glare-free" light provided that the region luminance did not cause visual discomfort. Uniformity of luminance across the ceiling plane (or the ratio of maximum: minimum ceiling zone luminance) was also interpreted to be a measure of visual comfort in so far as luminance contrasts over the depth of the room were minimized. To quantify the differences in luminance distribution between systems in terms of both magnitude and uniformity, a method was developed to compute the luminance of a number of unique, evenly-spaced regions defined by the room geometry. Region or zone luminance was computed by masking off the irrelevant pixels in the HDR luminance image then computing the average pixel value for the unmasked portion of the image. This was accomplished by post-processing the luminance images using a custom C-shell script to call a number of Radiance programs [6]. As illustrated in **Fig. 5**, the ceiling was subdivided parallel to the facade into six, 0.762 x 3.05 m (2.5 x 10 ft) regions. Each region was then symmetrically divided perpendicular to the facade to produce a total of 12 total regions. Because the overhead indirect lighting fixtures occluded a portion of the ceiling, the boundaries of affected regions were drawn to omit the fixtures. In addition, portions of ceiling regions that included objects such as cords (R3) or the ceiling supply air diffuser (L1, R2) were not included in the definition of the region. As a result of both the position of the camera lens (0.23 m, 0.75 ft from the interior face of the mullion) as well as the need to remove the ceiling diffuser, regions L1 and R1 are approximately half the depth of the other regions. A buffer of 3 pixels (indicated by the red lines in **Fig. 5**) was used to separate each region to avoid measurement errors from slight movements in camera position over the course of testing. Lines extended vertically downward to head height define additional wall regions but these were not used in this analysis.

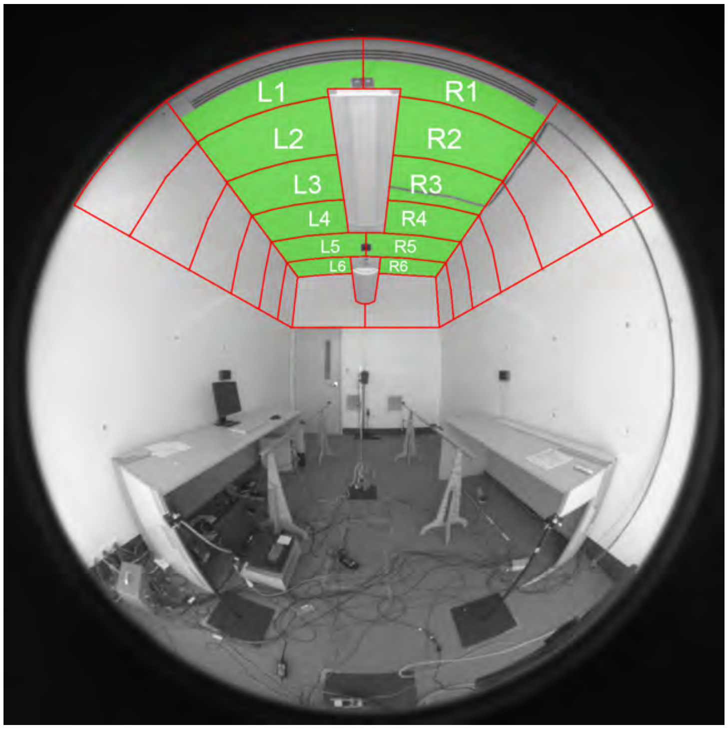

Fig. 5*. Image of test room with superimposed subdivision grid used to define individual ceiling regions for analysis. View is from the camera positioned at the facade looking towards the back wall of the test room.*

3. Results

3.1. Workplane illuminance and daylight autonomy

Fig. 6 compares seasonal performance between the OLS and the reference Venetian blind under clear sky conditions using the metric of daylight autonomy (DA). Data represent paired comparisons between systems under identical sky conditions. The performance of both systems was found to be related to the maximum daily altitude of the sun where, based on the DA criterion of 500 lux, the greatest DA conditions were achieved at the lowest sun angles and decreased significantly approaching the summer solstice (both systems recorded DA of 0% on June 20). Based on the 100 lux criterion, both systems performed more consistently as solar altitude varied. The performance of the Venetian blind increased approaching the summer solstice. This increase is partly due to the increased daylight hours as one approaches the summer solstice. Overall, the reference Venetian blind resulted in approximately 1.5 more hours of useful daylight per day on clear winter days with a low maximum solar altitude (<45°) and approximately 0.25 more hours of useful daylight on clear summer days with high maximum solar altitudes (>63°), given the 500 lux criterion. With the 100 lux criterion, the reference Venetian blind resulted in approximately 1 h and 2.5-6.0 h more of useful daylight for low and high maximum solar altitudes, respectively. For reference, this latitude had maximum solar altitude range of 29.5-76.5°. Performance under all sky conditions is summarized in **Tables 1-4**.

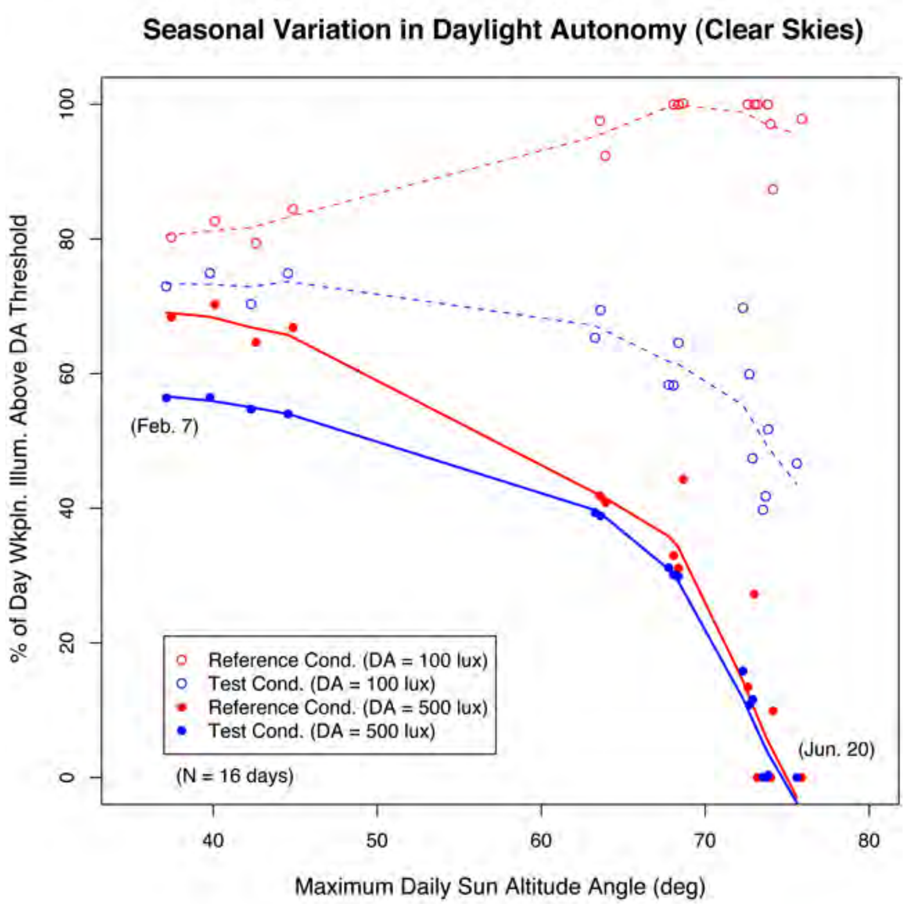

***Fig. 6**. Seasonal performance comparison based on daylight autonomy (DA) between the OLS (blue) and the reference Venetian blind (red) under clear sky conditions (6:00-18:00 ST). Two different criteria are set for DA. The solid circles/lines represent performance based on a DA criterion of 500 lux, the open circles/dashed lines represent performance based on a DA criterion of 100 lux. Workplane illuminance was measured at the back of the room.*

Table 1. Comparison in daylight autonomy achieved by day (6:00 – 18:00) under clear sky conditions.

Clear Skies		Test Condition (OLS)		Reference Condition	
Date (N = 16)	Max Altitude (deg.)	% of Day DA Achieved (100 lux)	% of Day DA Achieved (500 lux)	% of Day DA Achieved (100 lux)	% of Day DA Achieved (500 lux)
20100207	37.1	73%	56%	80%	68%
20100215	39.8	75%	56%	83%	70%
20100222	42.3	70%	55%	79%	65%
20100228	44.6	75%	54%	84%	67%
20100502	67.8	58%	31%	100%	33%
20100503	68.1	58%	30%	100%	31%
20100504	68.4	65%	30%	100%	44%
20100520	72.3	70%	16%	100%	13%
20100522	72.7	60%	11%	100%	27%
20100523	72.9	47%	12%	100%	0%
20100620	75.6	47%	0%	98%	0%
20100713	73.8	52%	0%	87%	10%
20100714	73.7	42%	0%	97%	0%
20100715	73.5	40%	0%	100%	0%
20100822	63.6	69%	39%	92%	41%
20100823	63.3	65%	39%	98%	42%

Table 2. Comparison in daylight autonomy achieved by day (6:00 – 18:00) under cloudy sky conditions.

Cloudy Skies		Test Condition (OLS)		Reference Condition	
Date (N = 4)	Max Altitude (deg.)	% of Day DA Achieved (100 lux)	% of Day DA Achieved (500 lux)	% of Day DA Achieved (100 lux)	% of Day DA Achieved (500 lux)
20100202	35.6	64%	22%	69%	37%
20100206	36.8	49%	9%	67%	23%
20100210	38.1	50%	18%	56%	34%
20100519	72.1	56%	7%	92%	40%

Table 3. Comparison in daylight autonomy achieved by day (6:00 – 18:00) under dynamic sky conditions.

Dynamic Skies		Test Condition (OLS)		Reference Condition	
Date (N = 3)	Max Altitude (deg.)	% of Day DA Achieved (100 lux)	% of Day DA Achieved (500 lux)	% of Day DA Achieved (100 lux)	% of Day DA Achieved (500 lux)
20100227	44.2	69%	31%	82%	55%
20100518	71.9	72%	9%	97%	40%
20100521	72.5	76%	8%	100%	52%

Table 4. Comparison in daylight autonomy achieved by day (6:00 – 18:00) under overcast sky conditions.

Overcast Skies		**Test Condition (OLS)**		**Reference Condition**	
Date (N = 7)	Max Altitude (deg.)	% of Day DA Achieved (100 lux)	% of Day DA Achieved (500 lux)	% of Day DA Achieved (100 lux)	% of Day DA Achieved (500 lux)
20100204	36.2	10%	0%	39%	0%
20100213	39.1	74%	22%	81%	64%
20100214	39.5	73%	50%	81%	63%
20100218	40.9	22%	0%	62%	1%
20100219	41.2	21%	0%	62%	1%
20100220	41.6	16%	0%	64%	1%
20100221	41.9	22%	0%	54%	0%

3.2. Discomfort glare from the clerestory window

Fig. 7 illustrates the seasonal variation in performance between the two systems under clear sky conditions based on the metrics of median (solid circle) and maximum (open circle) window luminance. Data represent paired comparisons between systems under identical sky conditions. A linear relationship was found between both the maximum and median daily window luminances of each system and the daily maximum solar altitude angle, where the magnitude of window luminance increased approaching the winter solstice. Because data was sampled at regular intervals between 6:00-18:00, the median indicates that conditions were equal to or "worse" than the median value for 6 hours each day. **Tables 5-8** provide summary data for all sky conditions.

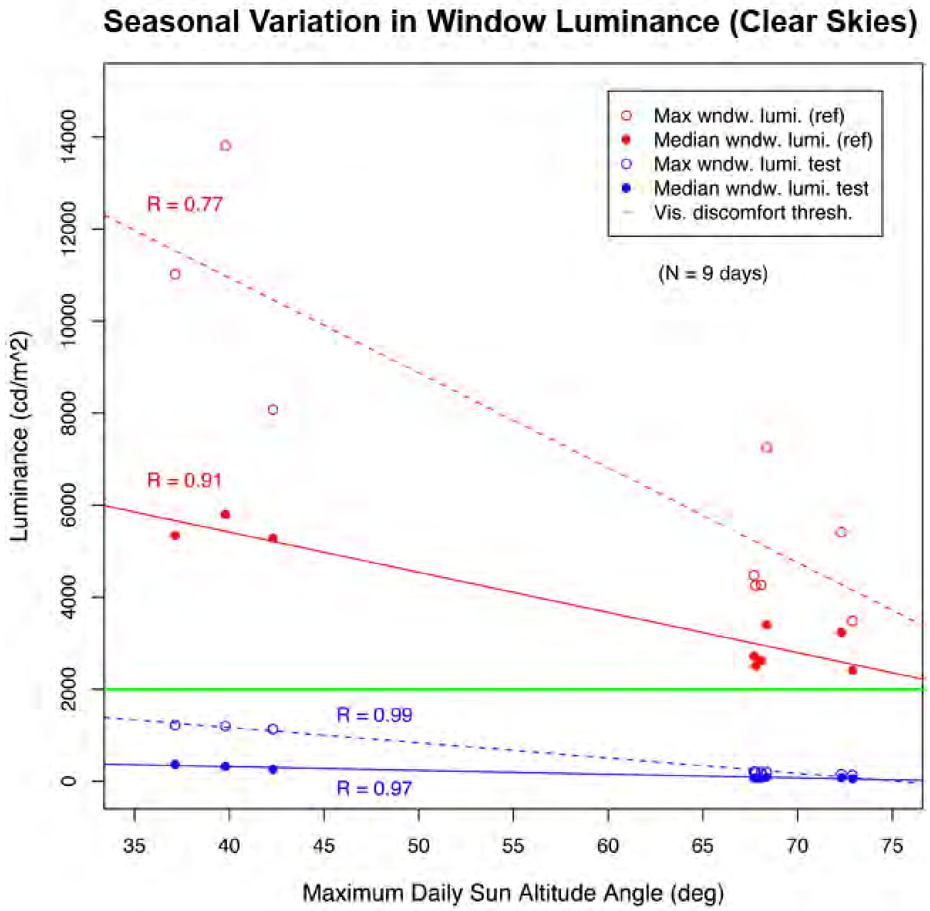

***Fig. 7**. Seasonal comparison of average clerestory window luminance between the OLS (blue) test system and the reference Venetian blind (red) under clear sky conditions based on median (solid circle) and maximum (open circle) luminance. Luminance was measured at a distance of 3.8 m (12.5 ft) from the window at seated eye height. The horizontal green line indicates the designated threshold for visual discomfort (2000 cd/m^2).*

Table 5. Seasonal variation in window luminance for OLS (test condition) and Venetian blind (reference condition) under clear sky conditions. "% Time Abv. (2000 cd/m^2)" indicates the percent of the 12-hour test period (6:00 – 18:00) when the average luminance of the clerestory exceeded the visual discomfort threshold 2000 cd/m^2. An 8000 cd/m^2 threshold is included to indicate extreme conditions.

Clear Skies		**Test Condition (OLS)**				**Reference Condition**			
Date (N = 9)	Max Altitude (deg.)	Median Lum. (cd/m^2)	Max Lum. (cd/m^2)	% Time Abv. (2000 cd/m^2)	% Time Abv. (8000 cd/m^2)	Median Lum. (cd/m^2)	Max Lum. (cd/m^2)	% Time Abv. (2000 cd/m^2)	% Time Abv. (8000 cd/m^2)
20100207	37.1	365	1218	0%	0%	5345	11023	71%	23%
20100215	39.8	325	1198	0%	0%	5798	13811	73%	38%
20100222	42.3	263	1135	0%	0%	5287	8080	71%	1%
20100501	67.7	76	207	0%	0%	2716	4479	69%	0%
20100502	67.8	71	202	0%	0%	2506	4256	61%	0%
20100503	68.1	70	198	0%	0%	2626	4267	64%	0%
20100504	68.4	92	200	0%	0%	3394	7255	72%	0%
20100520	72.3	82	154	0%	0%	3237	5413	68%	0%
20100523	72.9	59	138	0%	0%	2412	3487	67%	0%
								(Avg. = 68%)	

Table 6. Seasonal variation in window luminance for OLS (test condition) and Venetian blind (reference condition) under cloudy sky conditions.

Cloudy Skies		**Test Condition (OLS)**				**Reference Condition**			
Date (N = 5)	Max Altitude (deg.)	Median Lum. (cd/m^2)	Max Lum. (cd/m^2)	% Time Abv. (2000 cd/m^2)	% Time Abv. (8000 cd/m^2)	Median Lum. (cd/m^2)	Max Lum. (cd/m^2)	% Time Abv. (2000 cd/m^2)	% Time Abv. (8000 cd/m^2)
20100201	35.3	36	387	0%	0%	75	583	0%	0%
20100202	35.6	49	635	0%	0%	123	623	0%	0%
20100206	36.8	82	665	0%	0%	1969	14839	47%	6%
20100210	38.1	78	1030	0%	0%	1743	20573	42%	14%
20100519	72.1	59	237	0%	0%	2459	8713	58%	5%

Table 7.
Seasonal variation in window luminance for OLS (test condition) and Venetian blind (reference condition) under dynamic sky conditions.

Dynamic Skies		**Test Condition (OLS)**				**Reference Condition**			
Date (N = 3)	Max Altitude (deg.)	Median Lum. (cd/m^2)	Max Lum. (cd/m^2)	% Time Abv. (2000 cd/m^2)	% Time Abv. (8000 cd/m^2)	Median Lum. (cd/m^2)	Max Lum. (cd/m^2)	% Time Abv. (2000 cd/m^2)	% Time Abv. (8000 cd/m^2)
20100227	44.2	182	960	0%	0%	5229	11328	71%	12%
20100518	71.9	88	242	0%	0%	3306	8787	73%	8%
20100521	72.5	112	234	0%	0%	5028	8433	79%	3%

Table 8. Seasonal variation in window luminance for OLS (test condition) and Venetian blind (reference condition) under overcast sky conditions.

Overcast Skies		**Test Condition (OLS)**				**Reference Condition**			
Date (N = 7)	Max Altitude (deg.)	Median Lum. (cd/m^2)	Max Lum. (cd/m^2)	% Time Abv. (2000 cd/m^2)	% Time Abv. (8000 cd/m^2)	Median Lum. (cd/m^2)	Max Lum. (cd/m^2)	% Time Abv. (2000 cd/m^2)	% Time Abv. (8000 cd/m^2)
20100204	36.2	11	60	0%	0%	24	105	0%	0%
20100213	39.1	186	1248	0%	0%	4568	17038	73%	25%
20100214	39.5	268	1233	0%	0%	5262	15766	71%	36%
20100218	40.1	43	152	0%	0%	1138	4887	14%	0%
20100219	41.2	43	169	0%	0%	1199	5933	19%	0%
20100220	41.6	41	135	0%	0%	1177	3713	7%	0%
20100221	41.9	35	138	0%	0%	953	5128	18%	0%

3.3. Magnitude and distribution of daylight flux across the ceiling plane

Fig. 8 provides a visual comparison of the difference in daylight distribution in the room between the OLS and reference Venetian blind. Selected at a time of day when the surface solar azimuth was normal to the sourth-facing facade, the OLS is shown to distribute daylight more uniformly across the ceiling and walls perpendicular to the facade, as well as produce greater luminance levels at the back of the room. In contrast, the reference Venetian blind distributes roughly an equal amount of light to the walls as to the ceiling, and the transmitted light is concentrated on the surfaces immediately surrounding the window aperture. The upper back wall luminance is significantly greater than the reference case, indicating that had this been an open plan office, for which the OLS was designed, the flux would have been distributed much deeper than the physical limits of the test room (4.57 m, 15 ft depth).

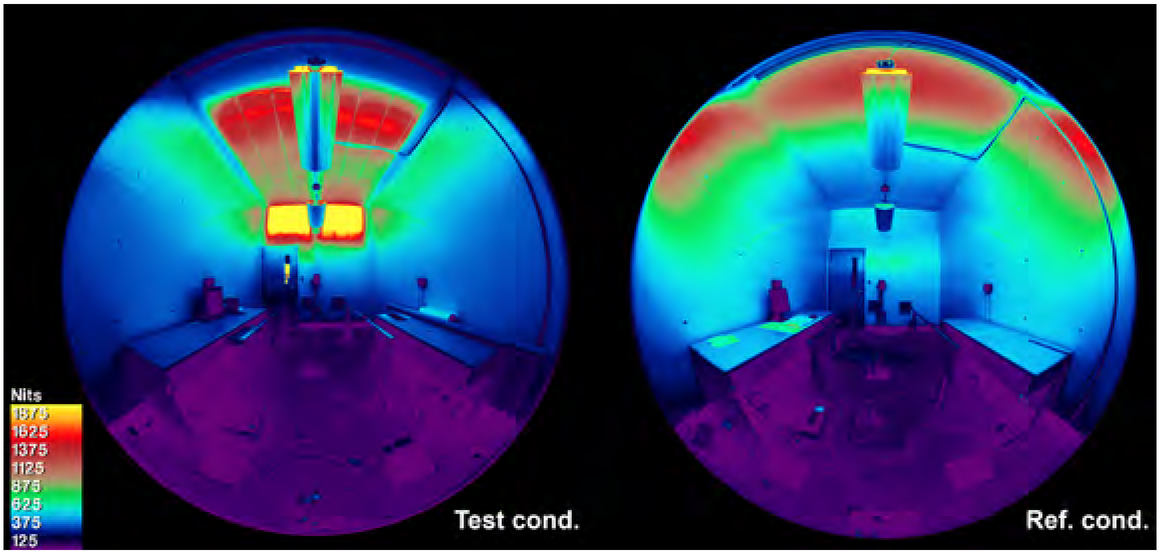

Fig. 8. *High dynamic range luminance map of test OLS condition (left) and reference Venetian blind condition (right), acquired near-simultaneously on February 7, 2010 at 12:22 ST (clear sky conditions) with falsecolor tone mapping (yellow indicates luminance ≥ 2000 cd/m²).*

Observations made for this single case extend to daily and seasonal performance for periods when the sun is near normal to the plane of the window and sky conditions are clear. **Fig. 9, 10** show the luminance for the ceiling regions over the 12-h hour test interval on a clear (February, 7) and overcast day (February, 21). The left and right sides of the six ceiling regions are shown on the same plot with the OLS profile shown in blue and the reference Venetian blind profile shown in red. The dotted horizontal blue and red lines indicate the average luminance of the OLS and Venetian blind respectively over the four-hour sub-intervals (6:00-10:00, 10:00-14:00, 14:00-18:00).

As illustrated by **Fig. 9**, the horizontal Venetian blind produced significantly greater ceiling luminances at zones adjacent to the facade (zones 1 and 2) than for the remaining zones (zones 3-6) under clear skies. In contrast, the OLS produced greater ceiling luminances towards the rear of the room. Referring to **Fig. 9**, the increased ceiling luminance of the OLS zone 6 is partially the result of additional light being reflected from the adjacent back wall. Relative to the Venetian blind, the OLS distributed an increasing amount of sunlight to zones 3 through 6 (55%, 69%, 100% and 153% more), respectively, on average during the 10:00-14:00 sub-interval. However, the OLS was comparable or “worse” than the Venetian blind over the other two sub-intervals.

Fig. 11 shows the resultant workplane illuminance levels over the same days shown in **Fig. 9, 10**. Daylight flux reflected off the ceiling and walls contribute to workplane illuminance. It is assumed that the lower view window will contribute daylight to the areas closest to the window. The upper clerestory window needs to supplement daylight levels in the rear of the office in order to justify its use. With a wall and ceiling surface reflectance of 85% and 86% respectively, the OLS was found to increase rear-zone workplane illuminance levels by 10% during the 10:00-14:00 period and reduce levels by approximately 35% during the other two periods (6:00-10:00 and 14:00-18:00) of the clear sunny day. Under overcast diffuse sky conditions, the OLS reduced rear-zone illuminance levels by approximately 50% compared to the reference case for each 4-hour period (**Fig. 11**).

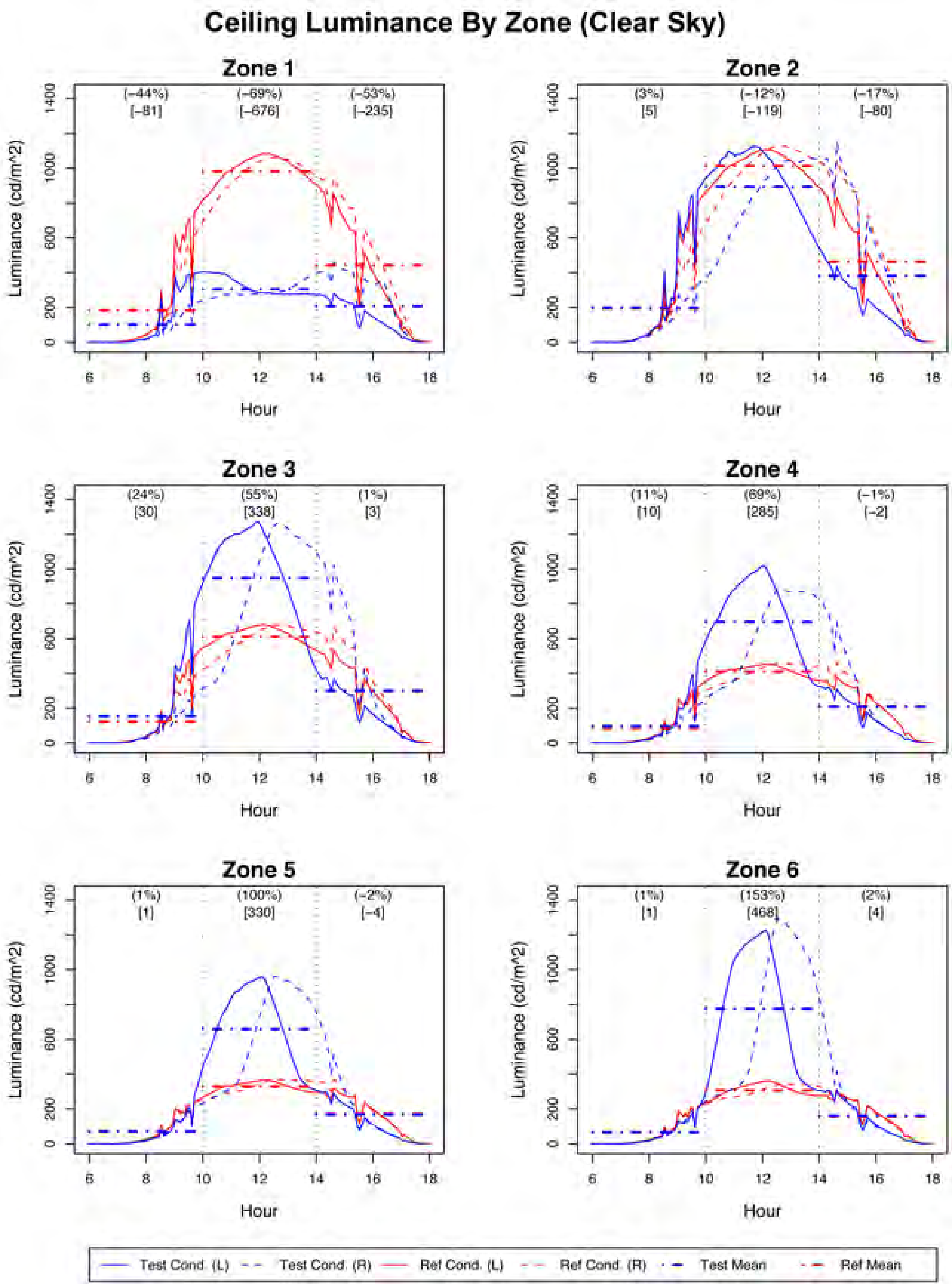

Fig. 9. *Comparison of ceiling luminance by zone between the OLS (blue) and the reference Venetian blind (red) under clear sky conditions on February 7, 2010. Numbers in parentheses indicate the percentage increase or decrease in average zone luminance (over each 4-h sub-interval) by the OLS over the reference Venetian blind. Numbers in square brackets indicate the average magnitude difference in cd/m². Zone 1 is closest to the window and Zone 6 is the farthest from the window.*

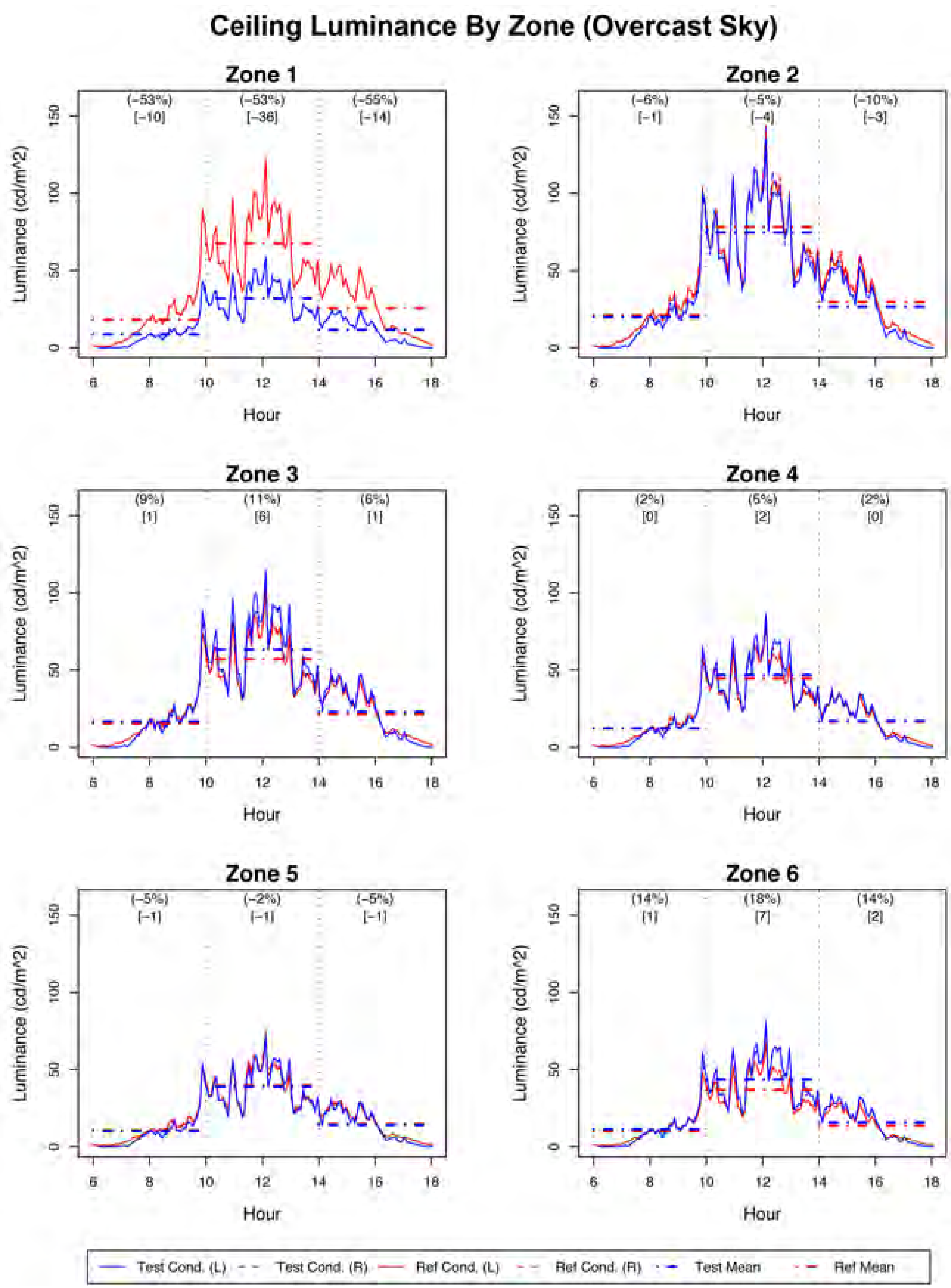

Fig. 10. *Comparison of ceiling luminance by zone between the OLS (blue) and the reference Venetian blind (red) under overcast sky conditions on February 21, 2010. Numbers in parentheses indicate the percentage increase or decrease in average zone luminance (over each 4-h sub-interval) by the OLS over the reference Venetian blind. Numbers in square brackets indicate the average magnitude difference in cd/m^2.*

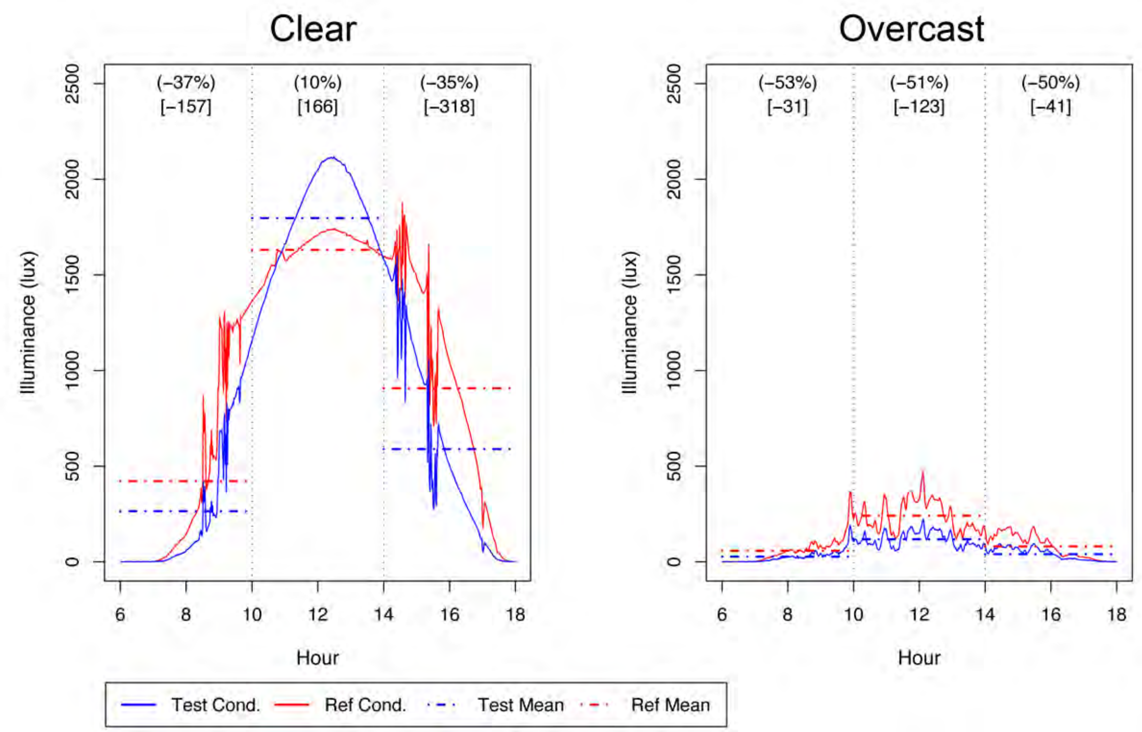

Fig. 11. *Left: Comparison of workplane illuminance levels between the OLS (blue) and the reference Venetian blind (red) under clear sky conditions on February 7, 2010. Right: Comparison of workplane illuminance levels between the OLS (blue) and the reference Venetian blind (red) under overcast sky conditions on February 21, 2010. Workplane illuminance levels represent the average between the two workplane sensors at the rear of the test room.*

Fig. 12 compares the OLS to the Venetian blind based on metrics of average ceiling luminance and uniformity between zones on average from 10:00-14:00 under clear sky conditions. Data summarize paired comparisons over (N = 14) days with clear sky conditions. The solid horizontal green line indicates the average luminance of ceiling zones 2 through 6. The dotted green lines indicate the maximum and minimum average zone luminances and the numbers in parentheses indicate the degree of uniformity between regions expressed in terms of a simple ratio of maximum:minimum. Due to the installation of the OLS at a distance of 0.53-m- (1.73-ft-) vertically from the ceiling, redirected sunlight never reached zone 1 directly (**Fig. 1, 2**). Therefore, the luminances recorded for zone 1 are not representative of the performance of the OLS in typical applications where it would be installed adjacent to the ceiling and thus, zone 1 was omitted from the analysis. The relatively lower luminance levels recorded for zone 1 are included in the sample daily ceiling zone luminance profiles shown in **Fig. 9**, **10**).

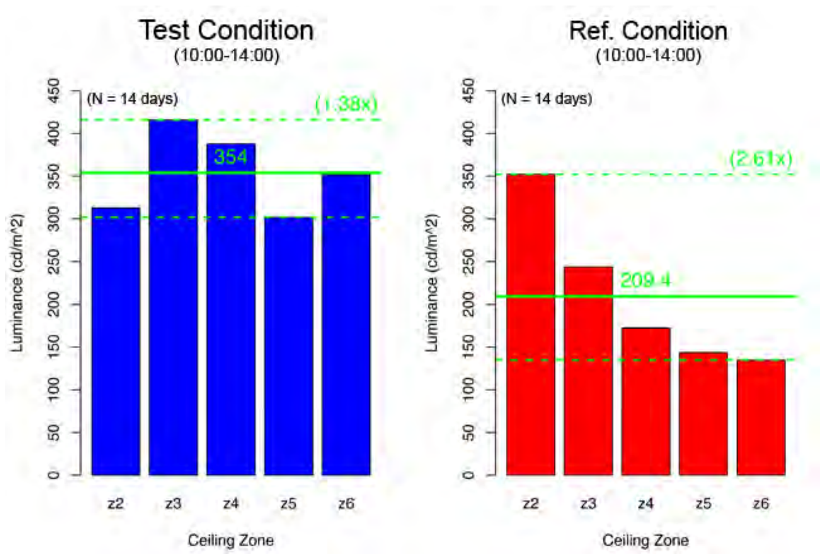

__Fig. 12__. Summary performance comparison between the OLS (blue) and the reference Venetian blind (red) under clear sky conditions based on average ceiling region luminance and region uniformity over the sub-interval 10:00-14:00 ST.

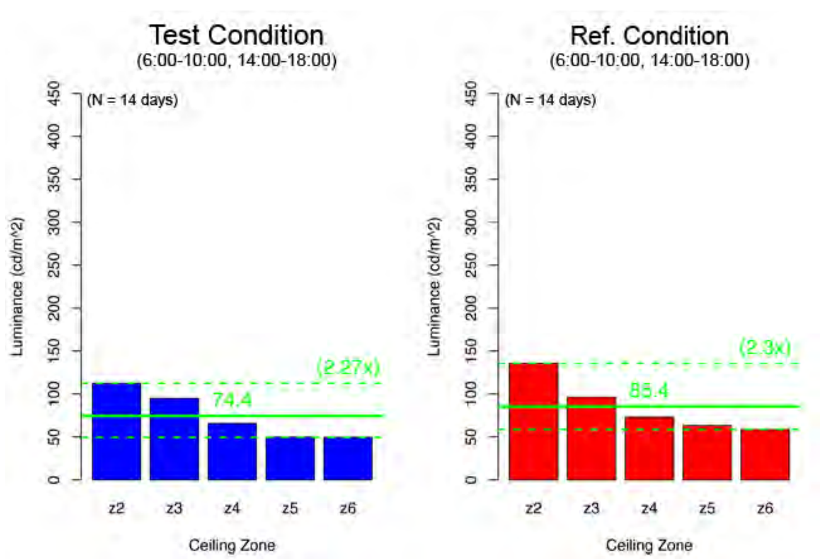

__Fig. 13__. Annual performance comparison between the OLS (blue) and the reference Venetian blind (red) under clear sky conditions based on average ceiling region luminance and region uniformity over the sub-intervals 6:00-10:00 and 14:00-18:00.

Based on the average of zones 2-6 over the monitored period, **Fig. 14** summarizes the percentage increase or decrease in ceiling luminance produced by the OLS compared to the Venetian blind. Data are given for each sky condition and for each of the three sub-intervals of the day. Due to the low number of total days for cloudy and dynamic sky conditions, results are likely to be illustrative rather than indicative of annual performance. The overcast sky condition is purportedly independent of solar position and is therefore indicative of annual performance. The results show that clear sky conditions produced the greatest increase in ceiling luminance during the middle of the day, with the remaining sky conditions following the same trend. For off-normal solar angles, the ceiling luminance of the OLS was less than that produced by the Venetian blind.

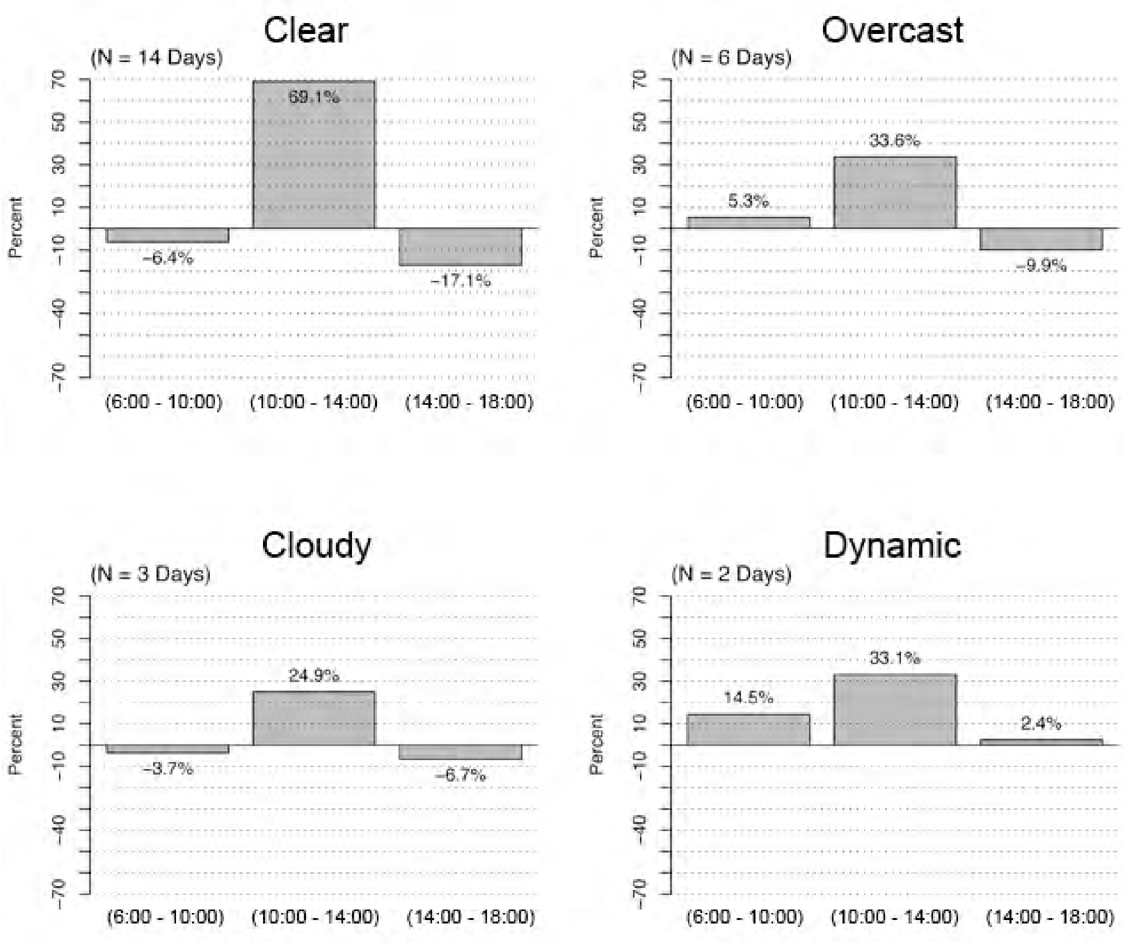

Fig. 14*. Percentage increase or decrease in overall ceiling luminance (average of zones 2-6) by the OLS relative to the Venetian blind reference per sky condition and four-hour sub-interval.*

4. Discussion

Because the OLS utilized specular surfaces to minimize light diffusion and a fixed geometry to redirect light to specific regions in the room, solar position had a strong effect on performance and illustrates the challenges for static light redirecting systems in achieving a consistent improvement in daylight autonomy over conventional systems. The results of the ceiling luminance analysis indicate that the OLS is capable of delivering significantly more light to the ceiling compared to the reference Venetian blind, and with a more uniform luminance distribution. Between 10:00 and 14:00 ST, the OLS produced significantly greater ceiling luminances on average (69%) under clear sky conditions and created a more even ceiling luminance distribution, where the greatest ratio between regions on average was 1.38, approximately half that of the Venetian blind (2.61). However, for the other two sub-intervals (6:00-10:00, 14:00-18:00) the performance of the OLS was comparable to the Venetian blind in terms of luminance uniformity and slightly worse in terms of average ceiling luminance.

Although the OLS did not perform as well in terms of hours of daylight autonomy (0.25 to 1.5 h less per day) as the Venetian blind (with slat angle set in a "best-case" condition for daylight transmission), results of the visual discomfort analysis show that the OLS produced significantly lower window luminance levels compared to the Venetian blind and never exceeded the designated visual discomfort threshold (2000 cd/m^2). In contrast, the median luminance for the reference Venetian blind exceeded the discomfort threshold for the entire test interval (**Fig. 7, Table 5**). Expressed in terms of time, the Venetian blind exceeded the discomfort threshold between 61% and 80% of the day under clear sky conditions over the test interval (68% average for N = 9 days, **Table 5**). In addition, near the winter solstice (Feb. 7, Feb. 15), the reference Venetian blind resulted significant periods of time when the window luminance exceeded 8000 cd/m^2 (23%, 38%) as well as large maximum levels (13,800 cd/m^2 on Feb. 15), which in a real building would have a high probability of causing occupants to adjust the blind slat angle to control discomfort leading to less daylight transmission relative to the "best-case" levels reported in this study.

The OLS was designed to extend the depth of daylight penetration and this particular shallow office test set-up did not allow one to evaluate this aspect of the system. One could speculate that the OLS performance without the intervening walls would have been more favorable at greater depths from the window. This aspect was studied in a companion simulation study [7].

5. Conclusions

This study demonstrates that optical sunlight redirecting systems located in the upper "clerestory" zone of the building facade can provide illumination levels comparable to a horizontal Venetian blind without the associated window glare, and can deliver a more uniform light distribution across interior surfaces.

Based on side-by-side comparisons of an optical louver system (OLS) and a conventional, matte-white Venetian blind with a horizontal slat angle located inboard of a clerestory window (WWR=0.174, Tv=0.62), daylight delivered by the OLS to the workplane at the rear of the room was found to be sufficient to achieve a minimum illuminance of 500 lux over 100% of the floor area for 56% of a 12-h day (February 7) to 0% of a 12-h day (June 20) under clear sky conditions in a south-facing, 4.6-m- (15-ft-) deep, private office mockup. With a 100 lux setpoint, daylight sufficiency ranged from 73% of winter solstice days (February 7) to 47% of summer solstice days (June 20).

Although the OLS produced fewer hours (between 0.25 to 1.5 h/day) of daylight sufficiency or daylight autonomy (DA) than the Venetian blind depending on the time of year, the OLS never exceeded the designated threshold for window glare (average luminance across window > 2000 cd/m^2). In contrast, the Venetian blind exceeded the glare threshold between 61% and 80% of the day under clear sky conditions over the test interval (68% average for N = 9 days) and produced levels above 8000 cd/m^2 for significant periods (23%, 38%) of winter days with low solar altitudes (February 7, 15). Further, the OLS was found to direct significantly more sunlight to the ceiling during the middle of the day (10:00-14:00 ST) compared to the Venetian blind (by 69% for clear skies; approximately 30% for non-clear skies) and to produce a more uniform luminance distribution across the ceiling. However, the daylight performance of the OLS was found to be comparable to, or worse than the Venetian blind for periods of time (i.e., 6:00-10:00, 14:00-18:00) when the solar surface azimuth was greater than the range of approximately ±45°.

Because conventional Venetian blind slats are often found to be in a far more closed position in real buildings to control window glare than the horizontal (i.e., "open") slat angle used in this study, in practical applications, static optical sunlight redirecting systems have the potential to significantly reduce the annual electrical lighting energy use of a daylit space and improve the quality from the perspective of building occupants by consistently transmitting daylight while eliminating window glare. In this study, the primary limitation found in achieving this goal is addressing decreases in performance as the surface solar azimuth angle increases relative to the facade normal.

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